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LAYERED OCEANIC MICROSTRUCTURE, ITS EFFECTS ON SOUND PROPAGATION

by

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1 FEBRUARY 1972

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Ola M. Johannessen*
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ABSTRACT

It has recently been established that the vertical profiles of oceanographic parameters in the seasonal and permanent thermocline regions are not the smooth curves observed by older techniques. Rather they indicate a large number of nearly homogeneous layers, with typical thicknesses of metres or less, separated by interfacial regions where strong gradients exist. Examples of typical layered microstructure profiles from different ocean areas are presented. The effects of such microstructure on sound propagation are examined qualitatively using ray tracing techniques. It was found that the layered microstructure had a significant effect only when rays vertex within the layers; in which case the iso-intensity-loss contours degenerate into a broad scatter of points.

*Authors listed alphabetically.

INTRODUCTION

The existence of thermal microstructure has been known for about 20 years [see, for example, Urick and Searfoss and Liebermann (Refs. 1 & 2)]. The results of Russian investigations, together with some of the more important contributions from "western scientists", have been summarized in a recent review by Gostov and Shvachko [Ref. 3] on "random inhomogeneities of microstructure of temperature and sound velocity profiles". More attention however has been paid to the so-called "patch size" microstructure of temperature and speed of sound fields (see, for example, Refs. 2, 4, 5, 6, 7, 8) than to the layered microstructure. Evidence of a layered microstructure, however, was reported by Piip [Ref. 9] in 1964, who measured some detailed vertical speed-of-sound profiles in the Bermuda area. Figure 1 shows an example of one of these profiles. Actually two profiles are shown, one displaced 25 cm/s to the left. Thin layers of lower speed, a few metres thick, are seen in the main thermocline. Piip referred to these layers as "strange layers of water" and we shall see that this is what is presently called layered microstructure.

In this report some typical vertical temperature, salinity and speed-of-sound profiles are shown to illustrate the layered microstructure. In order to obtain some qualitative understanding of how this layered microstructure can affect the propagation of sound, ray tracing was performed using speed-of-sound profiles both with microstructure and with microstrucrure smoothed.

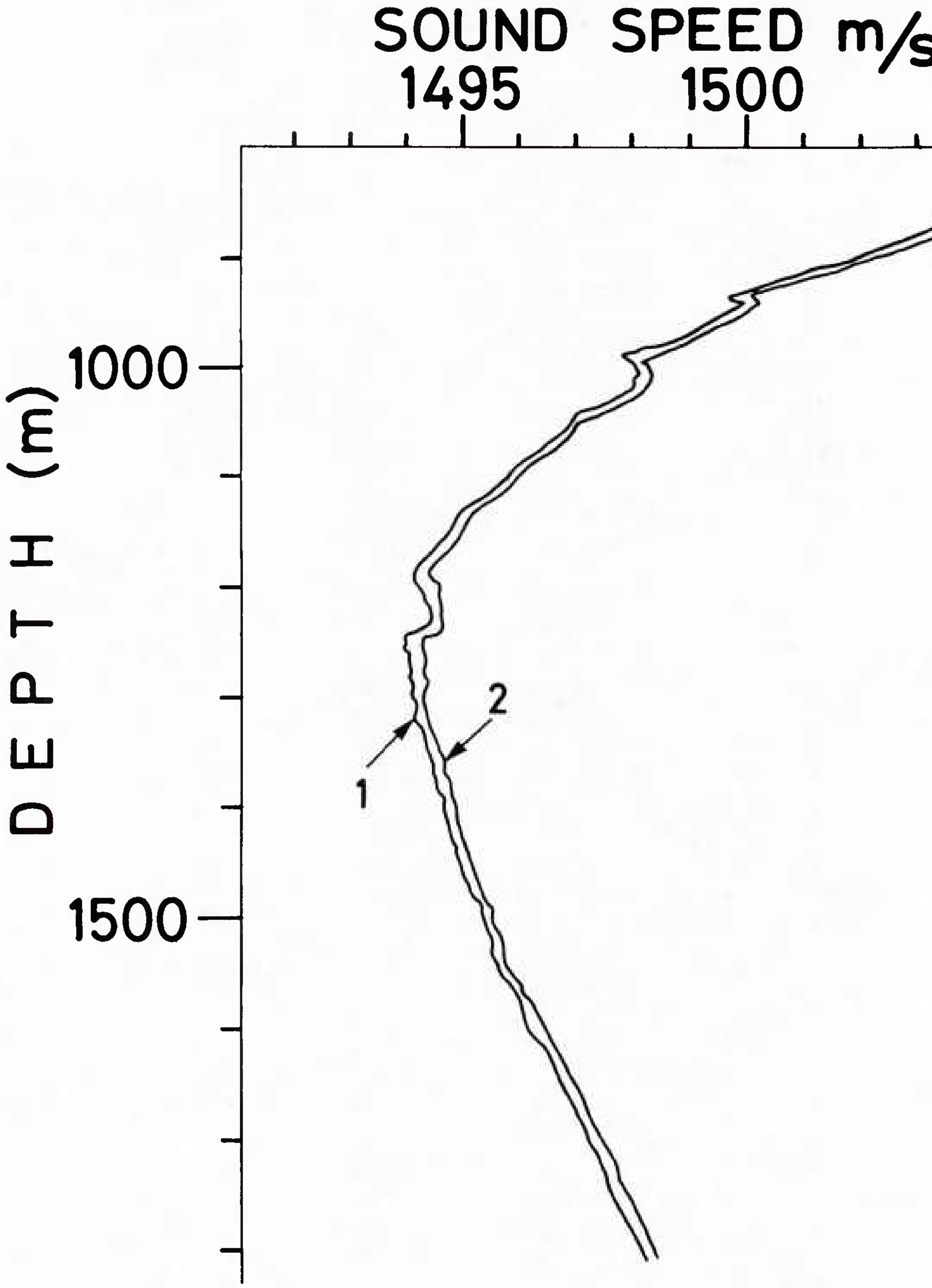


FIG. 1 TRACKING OF TWO INDEPENDENT VELOCIMETERS. CURVE 1 SHIFTED 25 cm/s TO LEFT (From Piip, Ref. 9)

1. LAYERED MICROSTRUCTURE

The study of layered microstructure has recently attracted the attention of physical oceanographers. Such investigations have been possible due to the introduction of the STD* system which continuously records temperature and salinity versus pressure, and to the use of specially designed free-falling microstructure probes. Observations with these instruments have shown that the vertical profiles of the oceanographical parameters are not smooth, as normally deduced from traditional Nansen cast data, but rather exhibit a number of both regular and irregular nearly homogeneous layers with typical thicknesses of metres or less, separated by interfacial regions or transition zones where large gradients are present.

Figure 2 shows a somewhat schematic example of layered microstructure in the thermocline observed east of Malta by Woods [Ref. 10] using a free-falling microstructure probe. For every meter both temperature, and the temperature gradient determined as the difference between two thermistors separated by 25 cm in the vertical, are recorded. The layering effect is clearly established in the thermocline. Separating the nearly isothermal layers, which are of the order of 2 m – 4 m thick, are interfacial regions, or as Woods calls them "thermocline sheets", where changes of 0.2°C – 0.4°C occur.

The investigators who study microstructure experimentally can be divided into two main groups; one uses commercially available STD systems with a vertical resolution of about 0.5 m – 1 m depending on the sea state, the other using prototype free-falling

* STD denotes Salinity, temperature and depth sensors ; STDV denotes the addition of a sensor to measure the speed-of-sound.

microstructure probes, not available on the commercial market, with vertical resolution of one cm or less. This vertical resolution enables the study of the finer structure in the temperature field. In the Western world the latter group is, for example, presented by Woods [Refs. 10 & 11], Woods and Wiley [Ref. 12], Cox et al [Ref. 13], Grant et al [Ref. 14] and Nasmyth [Ref. 15]. The papers by Stommel and Fedrow [Ref. 16], Cooper and Stommel [Ref. 17], Grafe and Gallagher [Ref. 18], Siedler [Ref. 19], Tait and Howe [Ref. 20], Howe and Tait [Ref. 21] are examples of the STD group. A modified XBT system has also been used by Neal et al [Ref. 22] in studying microstructure in the Arctic ocean. In the light of the results from the microstructure probe group it becomes clear that only the larger scale layered microstructure is observed by the group using the STD because of the limited vertical resolution of this instrument. [See also a recent review article on Oceanic Microstructure by Cox (Ref. 23)].

Figure 3 shows a recent profile after Woods and Wiley [Ref. 12] east of Malta, with increased resolution when compared with the profile in Fig. 2. In Fig. 3 the profile is measured continuously and the gradient is measured over a 10 cm interval. Both the temperature trace and the gradient are more irregular than in the previous figure. The interfacial region between the isothermal layers which previously was thought to consist of one "thermocline sheet", now appears to consist of several sheets [Woods, Ref. 12]; the thickness of the nearly isothermal layers is of the order of 1 m - 2 m or less. Figure 4 shows, for the same area, a temperature and speed-of-sound profile obtained by one of the authors with an STDV instrument; the layering effect is clearly established but this instrument fails to resolve the finer detail shown on Fig. 3. The layering, which is strong in the thermocline region, decreases with depth.

The last three figures were all from one area in the Mediterranean. Figure 5 shows successive STD analogue traces observed during a 20 min period from a drifting ship south of Bermuda in the Atlantic Ocean [Cooper and Stommel, Ref. 17]; the arrows indicate the direction of the probe. It is seen that some detail is lost when the probe is on its way up, this is caused by unequal exposure of the sensors in opposite directions. Rather regular, isothermal layers, about 5 m thick, can be seen, separated by transition regions of 10 m - 15 m where the temperature and salinity (not shown) change by 0.3°C - 0.5°C and 0.04‰ - 0.10‰ respectively. From several STD dips in the area it was generally found that about one hundred of these layers occurred in the main thermocline.

Observations from the Pacific (for example, Refs. 16, 18, 13, 15) also show the existence of layered microstructure. In particular Cox et al [Ref. 1], using a free-falling probe with vertical resolution of one cm, observed that, at depths between 400 m and 600 m, the temperature trace consisted of an "irregular series of sharp delta function spikes of temperature gradients superimposed on a continuum of temperature unrest". Furthermore, large numbers of unpublished STD observations held by different laboratories around the world show that the layered microstructure is a common feature of the thermocline region.

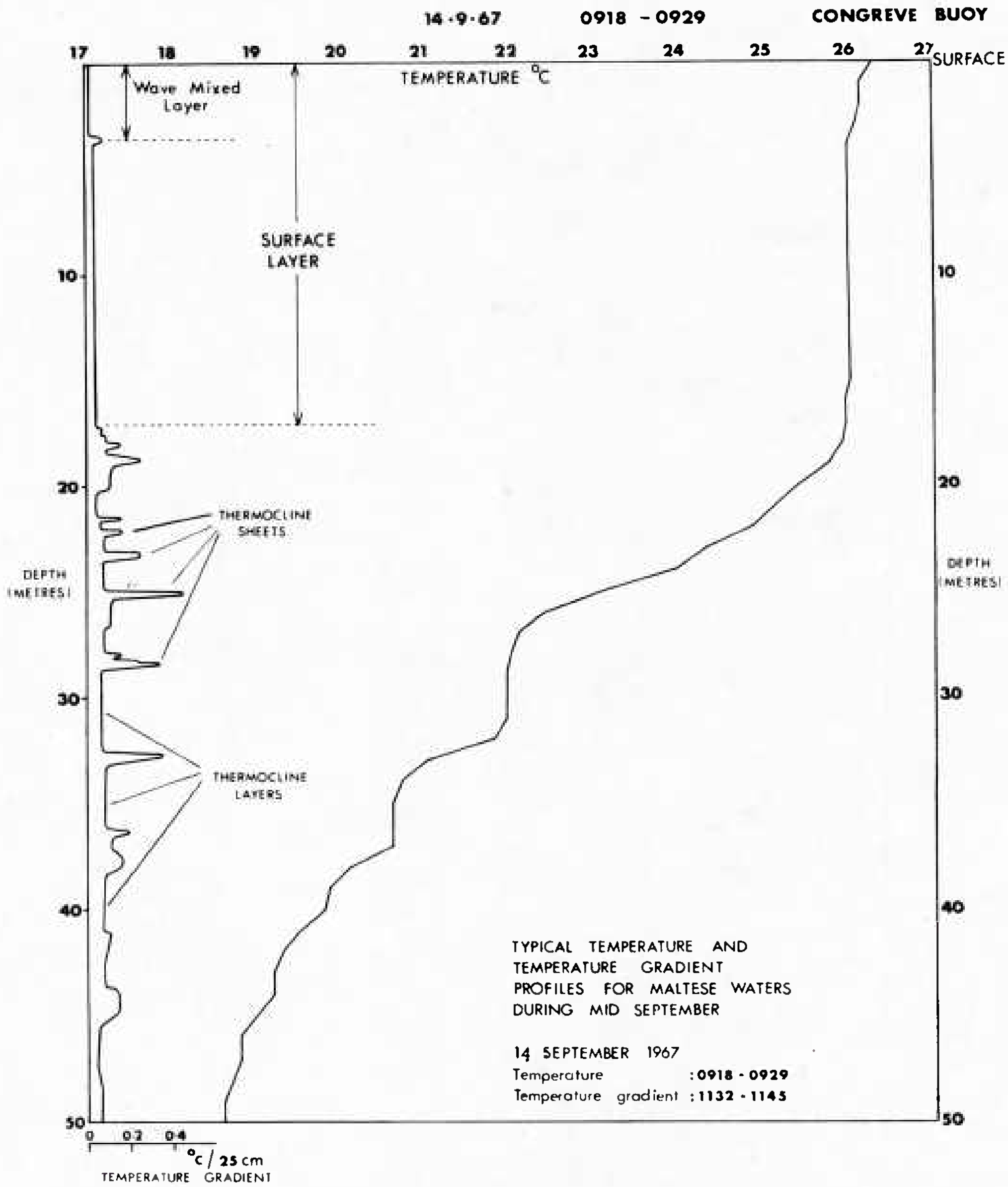
Few investigations, however, consider in detail the horizontal extent, variability and generation of layered microstructure. Some preliminary results show that the same layer can extend from a few hundred metres to tens of kilometres in the horizontal [Refs. 11, 13, 15, 16, 17, 18]. Furthermore the layers move up and down with the internal waves present in the thermocline region. Several mechanisms for the generation of layered microstructure have been proposed, such as breaking internal waves, formation of layers at boundaries (such as an oceanic front) followed by spreading along density surfaces and a double diffusion process, also referred to as the "salt fingering" process. However, at present, the generation mechanism(s) is not fully understood.

So far, only layered microstructure in the thermocline region (seasonal and permanent) have been mentioned. However, a stepped structure even more pronounced has been established in the deep part of the ocean. Figure 6 shows such a stepped structure located just below the intrusion of the high saline Mediterranean water, in an area between Gibraltar and Madeira in the north east Atlantic [Tait and Howe, Ref. 20]. The thickness of the layers was of the order of 15 m - 30 m and changes across the interfaces between the layers were of the order of 0.25°C and 0.044‰ for temperature and salinity, respectively. Unfortunately no observations were made below 1500 m, but probably the layering would extend to larger depths. A more detailed study of the variability of the layers was also performed in the same area by Howe and Tait [Ref. 21]. The upper part of Fig. 7 gives some results: the average thickness of the layers and interfaces and also the changes in oceanographic parameters across the interfaces. The lower part of Fig. 7 shows the time variability at one location over a 33-hour period. It is clearly seen that the layers are taking part in the internal-wave oscillation. Spatial investigation showed that the layers extended for about 20 n.mi in the horizontal.

Similar deep stepped structure has been observed in the Tyrrhenian Sea by Owen S. Lee from NUC, San Diego (unpublished data). Figure 8 shows one of the STDV stations and the stepped structure starting to form just below the highly saline Levantine water. In the upper part the thickness of the layers is of the order of 15 m - 20 m. This thickness increases with depth to as much as 200 m, between the depths of 1100 m and 1300 m. Below 1600 m - 2000 m, the stepped structure is not apparent. Figure 9 shows a magnification of the profiles; for example, the change in the speed-of-sound across the interfaces is of the order of 0.2 m/s to 0.3 m/s. Deep stepped structure has also been established west of the Strait of Sicily by one of the authors; the structure however was not as pronounced as in the two cases previously mentioned.

All these profiles show that the stepped structure started to form below the region where maximum salinity occurred and the temperature was decreasing, an oceanographic condition which favours a so-called "salt finger mechanism" which may be a reason for formation of the layers [Ref. 24]. Stepped structure of a similar kind has also been established in the Arctic Ocean [see Fig. 10 after Neal et al (Ref. 22)].

In summary, one can say that a deep stepped structure has so far been established only in special areas, and probably it is by no means as common as the smaller scale layered microstructure in the thermocline region.



A typical sounding through the summer thermocline off Malta during mid September

FIG. 2 MICROSTRUCTURE TEMPERATURE PROFILE (From Woods, Ref. 11)

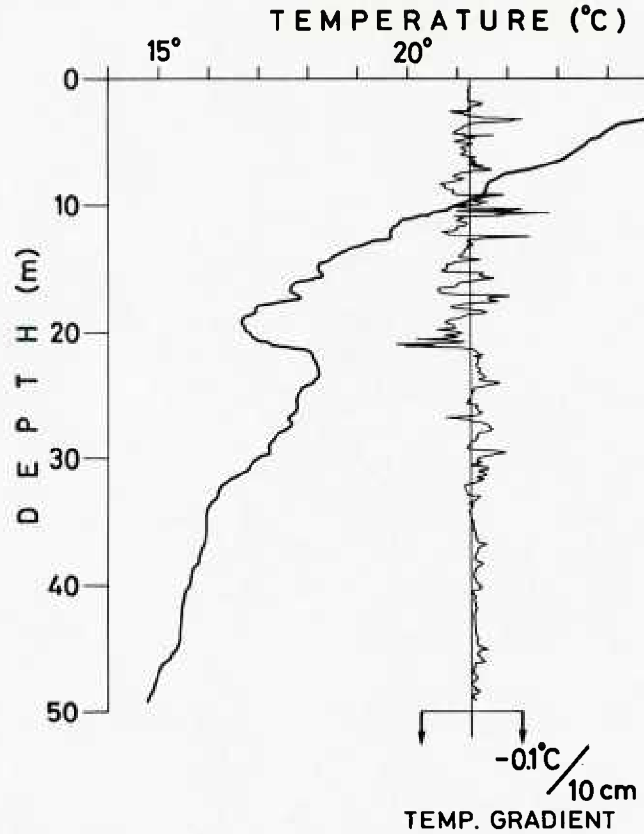


FIG. 3 MICROSTRUCTURE TEMPERATURE PROFILE (From Woods and Wiley, Ref. 12)

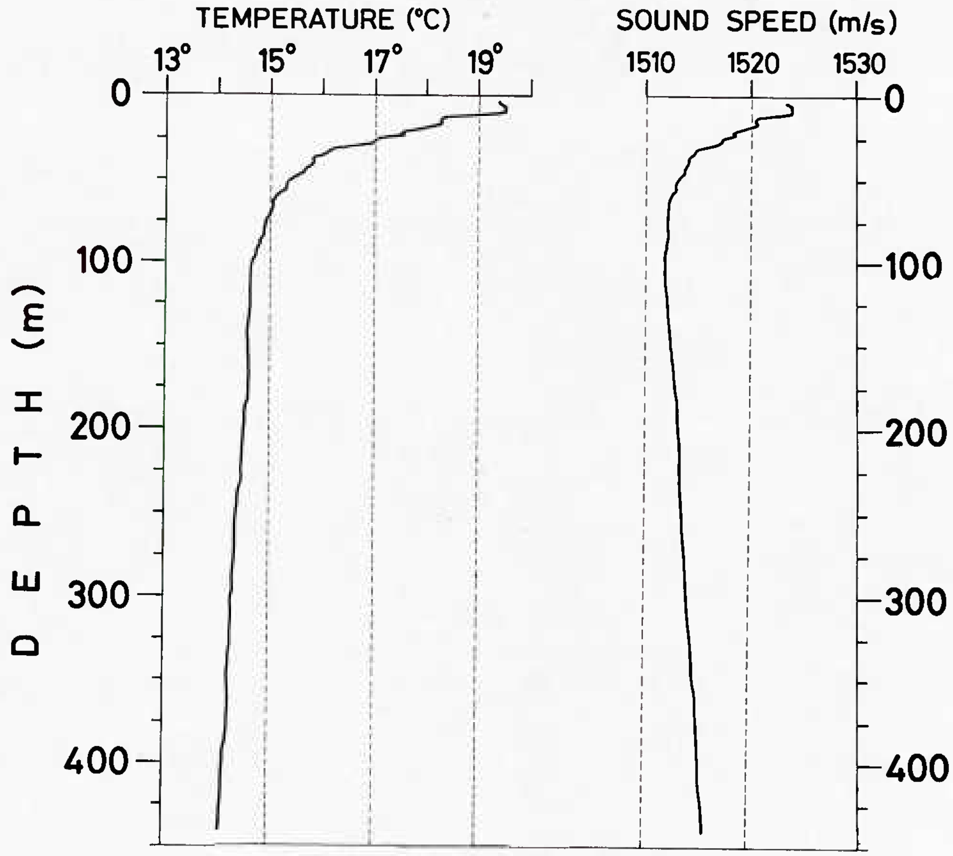


FIG. 4 STDV OBSERVATIONS EAST OF MALTA, SACLANTCEN 1971

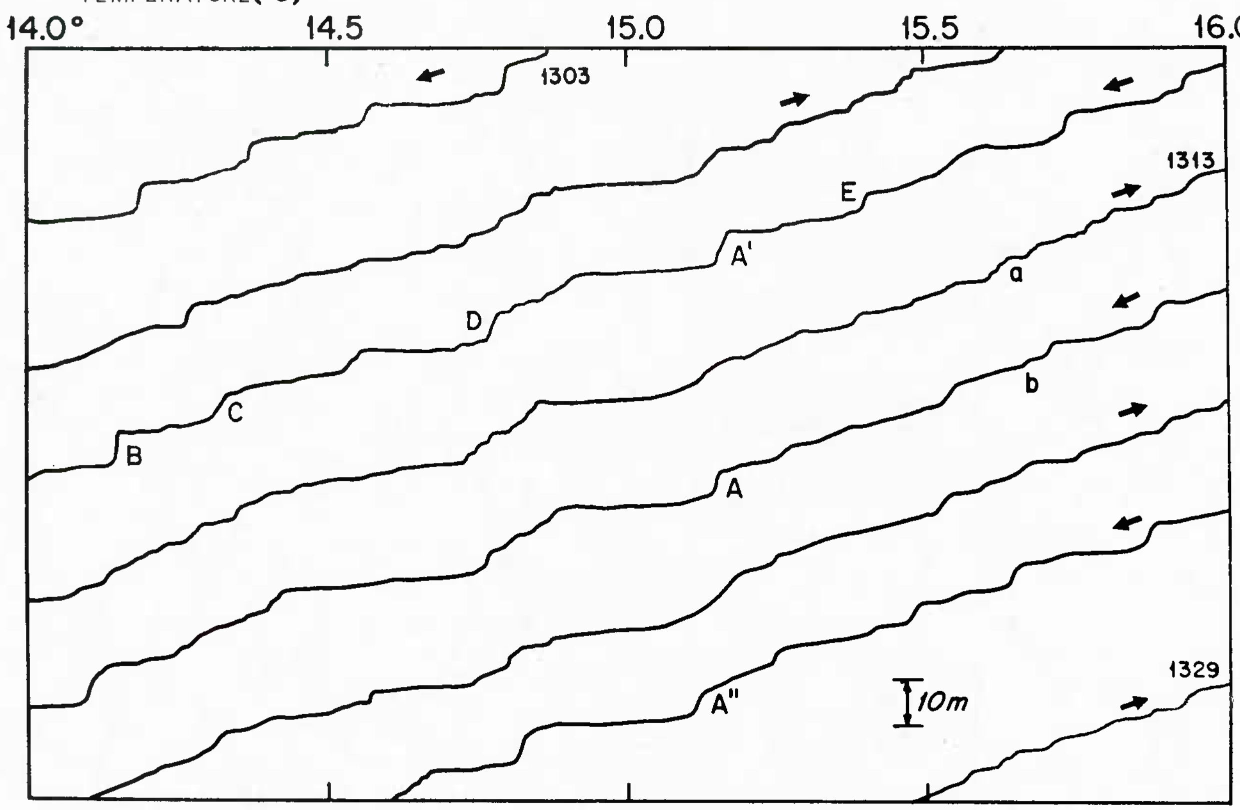


FIG. 5 SEVERAL SUCCESSIVE TEMPERATURE SOUNDINGS WITHIN THE UPPER PART OF THE MAIN THERMOCLINE (From Cooper and Stommel, Ref. 17)

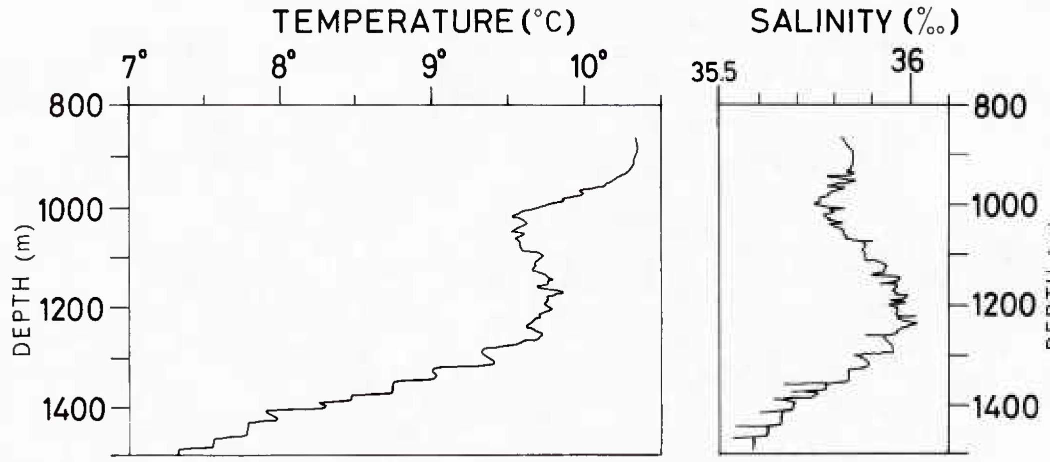
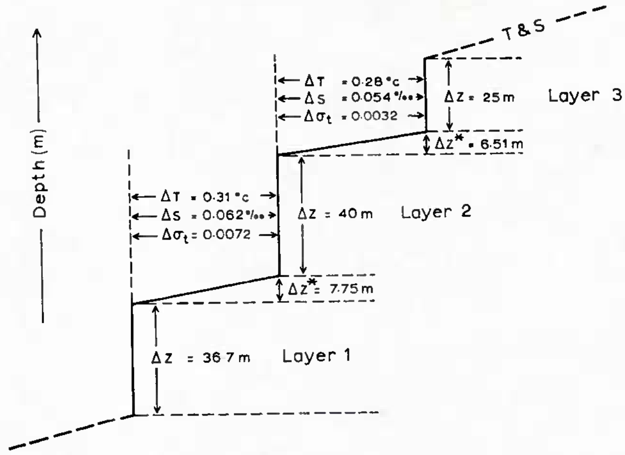
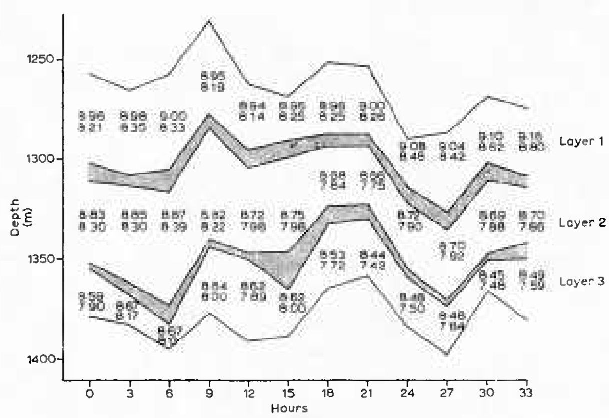


FIG. 6 STD RECORD FROM 34°21'N. 13°30'W (From Tait and Howe, Ref. 20)



Average parameters for the 3 layers considered in the analysis, computed from 33-hr of observation at a single station.



Depth variations of the layer system for Series A. Shading denotes interfaces and mean values of T and S within each layer also shown (S to three decimals after 35‰).

FIG. 7 VARIABILITY OF DEEP LAYERED STRUCTURE (From Howe and Tait, Ref. 21)

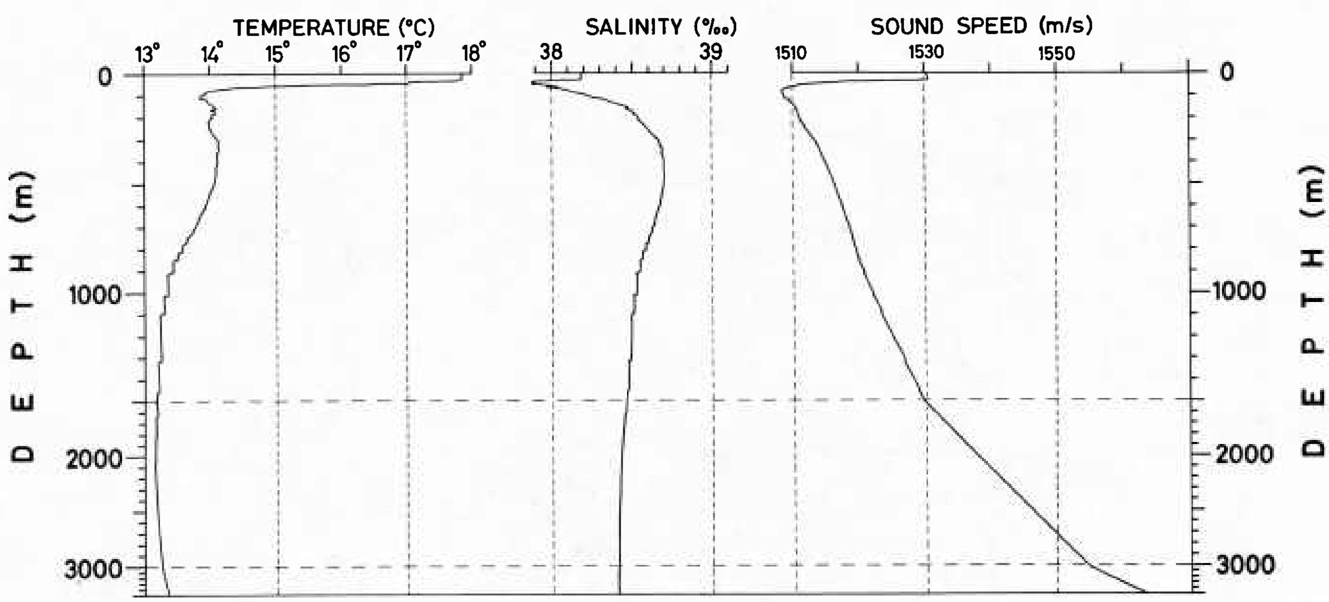


FIG. 8 STDV RECORD FROM THE TYRRHENIAN SEA (From O.S. Lee, 1971)

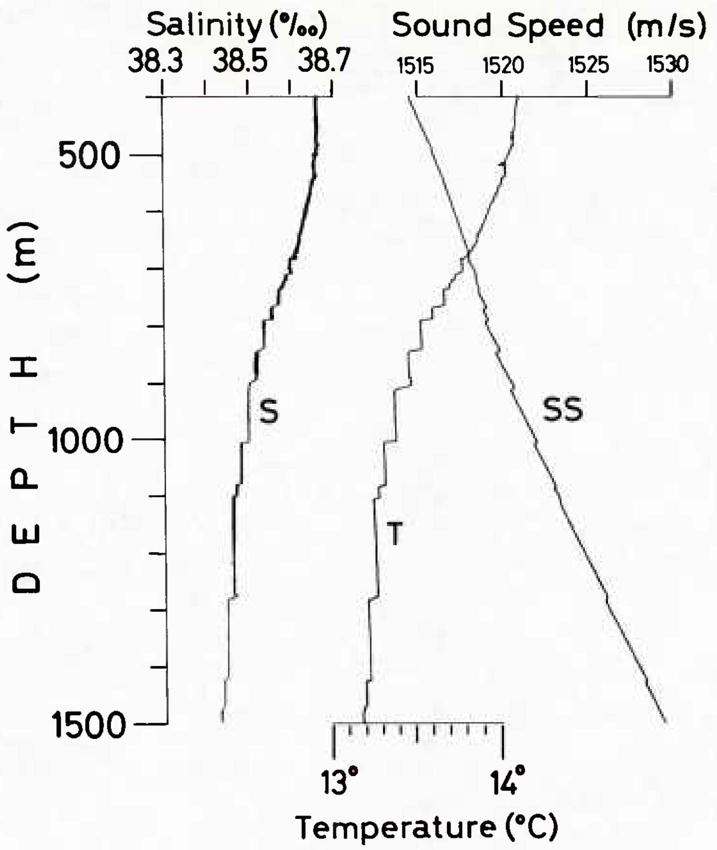


FIG. 9 MAGNIFICATION OF STDV RECORD SHOWN IN FIG. 8 FROM TYRRHENIAN SEA

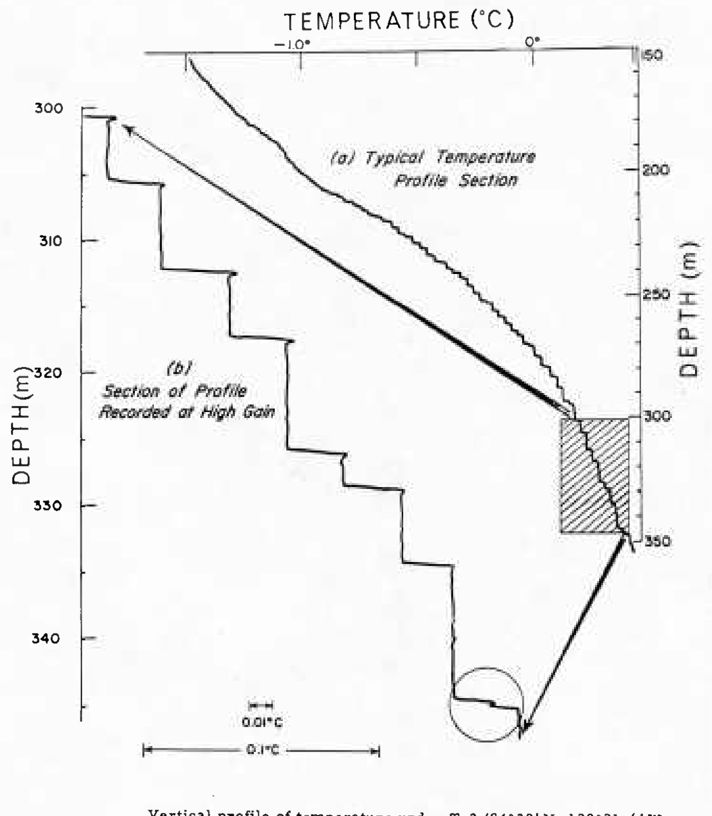


FIG. 10 VERTICAL PROFILE OF TEMPERATURE UNDER T-3 (84°38 N, 128°21 6 W, 19 MARCH 1969). Shaded section of profile (a) shown as observed in profile (b) to left. (From Neal et al, Ref 22)

2. ACOUSTIC EFFECT

The influence of layered microstructure upon sound propagation is dependent on the speed-of-sound gradients, and the physical size, shape and dynamics of the microstructure. The ranges of variation of these quantities are such that the problem does not lend itself very readily to a general quantitative solution. The results of a qualitative study using ray tracing techniques are given in this section.

A simplified Bermuda profile as shown in Fig. 11 was chosen. Then, using the results from Cooper and Stommel, [Ref. 17, Fig. 5], for the Bermuda area, a second Bermuda profile was prepared. As shown in Fig. 11, a layered microstructure was inserted in the main thermocline, using layers of thickness of 5 m, and transition zones of 10 m in which the temperature changes by 0.3°C. For simplicity the salinity was held constant, although in reality similar steps generally also occur in the salinity profile. The layered microstructure may also exist in the seasonal thermocline, however again for simplicity it has been omitted. The ray tracing technique used in this study assumes that the layers extent infinitely in the horizontal direction although, as pointed out earlier, they are limited horizontally.

Ray tracing was performed for source depths of 5 m, 125 m, 890 m and 1200 m. Iso-intensity loss contours for geometrical spreading were also plotted.

No significant changes in the iso-intensity loss contours were noted when the results from the two profiles with and without microstructure were compared for the source depths of 5 m and 125 m. The sources at these depths are located above the microstructure. The influence on such source depths when the microstructure exists in the seasonal thermocline is examined later in this report.

For the source located at the depth of 890 m, that is in the middle of the microstructure, a significant change occurred in the iso-intensity contours. The ray tracing for this source depth, using only the profile with the linear thermocline, is presented in Fig. 12. The increment in angle between rays at the source is 1°. Positive source angle rays are measured downward from the horizontal, negative upward. Also presented in the figure are two sets of 75 dB iso-intensity loss contours for geometrical spreading. One set corresponding to the profile with the linear thermocline and the other set corresponding to the profile with the layered microstructure in the thermocline. The position of the contours for the negative angle surface reflected and positive angle rays is the same for both profiles. However, for the negative angle rays that vertex in the thermocline a change has occurred. The nearly vertical line is the contour for the profile with no microstructure. For the profile with the microstructure the contour is scattered into iso-intensity points (shown as dots) over more than 4 km of range.

This scatter of points becomes clearer in Figs. 13 and 14 which are enlargements of that part of the area where the 75 dB contour exists [Fig. 12]. The increment in angle between rays at the source is now decreased to 0.5°. The bundle of rays plotted can be divided into three families. On the figure, the 0° ray has not been plotted, so the blank space for its position serves to distinguish between rays of positive and negative source angle. The speed-of-sound profile used, that is shown in Fig. 11 has a surface layer with a positive gradient. This produces the so-called split-beam ray. This ray vertexes at the bottom of the positive surface layer and can be refracted upward and downward; there is a divergence of energy away from this depth. This ray also has not been plotted but the position of it is indicated in the figure by symbol θ_s. This space serves to divide the negative angle rays into two families; those above the split-beam ray reflect from the sea surface, those below remain in the thermocline and vertex in it. We shall refer to this latter family as thermocline vertexing rays. In Fig. 13 the iso-intensity loss contour for each of the three families of rays are fairly smooth curves. The spacing between rays remains fairly regular.

The iso-intensity contours in Fig. 14 for the microstructure profile are smooth and their position barely changed for the direct and surface reflected rays. The thermocline vertexing rays however display, and are the source of the dispersed iso-intensity points we observed in Fig. 12. The spacing between rays for this family is uneven.

The layered type of microstructure in our profile has its greatest effect upon these rays after they vertex in it. The reason is not only that these rays vertex in the microstructure but that they separate into groups at the bottom of the positive layer in each step; this is the same separation we observed at the bottom of the positive surface layer in Fig. 13. At each of these points, some of the rays continue upwards and others are refracted downwards. The resultant effect is the uneven spacing between rays as seen in Fig. 14 and the concomitant scatter of the iso-intensity points.

Rays of positive source angle can also vertex in the layered microstructure in this model and a similar effect would be noted. However, since they vertex at greater ranges, they will affect the intensity contours of higher value losses not presented in this figure.

The effect of the microstructure upon the rays of a source, at a depth 1200 m is seen in Fig. 15. The loss contours for both profiles are both indicated. We can see that again the smooth iso-intensity contour for rays that vertex in the thermocline has been dispersed over an area into iso-intensity points (circles). The effect upon the curves associated with all other types of rays has been negligible.

Similar results were obtained for other values of acoustic intensity. Figure 16 is an example. The circles are the 75 dB intensity loss points and the crosses are the 80 dB loss points for the source at 1200 m. It can be seen that the points are mixed to some extent indicating that at least a 5 dB fluctuation in intensity can occur in the sound field over small increments in range and depth. The points are dispersed in the range interval between approximately 4 and 8 km.

A similar examination was made for an observed Mediterranean Sea profile, after Woods Fig. 3, that exhibited the layered microstructure. The profile was recorded in the first 50 m, and for simplicity we assume the temperature is constant below this depth. A detailed approximation to the actual profile is given in Fig. 17A, and two profiles with simpler approximations (more smoothing) to the detail of the microstructure are given in Figs. 17B and 17C.

Figure 18 gives the ray tracing for the simplest profile, C of Fig. 17. The source depth is 150 m and the angle increment is 0.1°. The 75 dB iso-intensity loss points are also plotted, they form a contour segmented into three parts. The lower segment corresponds to rays reflected from the sea surface, the two upper segments correspond to rays that have vertexed in the thermocline.

Figure 19 shows the results of the second approximation to the microstructure detail, (profile B of Fig. 17). It can be seen that the contour segment for the family of rays that reflect from the surface is unchanged. For the thermocline vertexing rays, however, the two previous contours are broken up into five segments.

Figure 20 is the ray tracing for the detailed profile, A in Fig. 17. The iso-loss contours are now dispersed into iso-loss points as occurred in Fig. 12 for the simplified Bermuda profile. The reason is that, in both speed-of-sound profiles, the same qualitative layering exists, and affects the rays in a similar manner.

In order to obtain some indication of the fluctuations that could occur a plot was made of propagation loss versus range at a depth of 300 m for the 150 m source depth using both the smoothed profile B and the detailed profile A in Fig. 17. The results are given in Fig. 21. The open symbols represent points for the smoothed profile, the solid symbols are for the detailed profile. The smoothed profile has resulted in six families of points and corresponds to the rays that formed the six segments of the iso-intensity loss contour plotted in Fig. 19. It can be seen that the detailed profile produces a considerable scatter of the points with changes in loss greater than 10 dB occurring over short distances. The portion of the plot where the points (square symbols) are coincident for both profiles occurs for surface reflected rays. The other points correspond to rays that have vertexed in the microstructure.

The deep layered stepped structure observed well below the thermocline region and the axis of the deep sound channel [Fig. 8] will have a different influence on the sound intensity with respect to the depth of the source than the layers found in the thermocline. Sources located near the sea surface can now generate rays that will vertex in the layers. The influence upon these deep refracted rays will be felt in the convergence zone measurements. The magnitude of the effect will depend upon the speed of sound at the source and within the layers. These factors dictate the size of the bundle of rays that will vertex in the layers. To have any rays vertex in the layers, the maximum sound speed in the layers must be greater than the sound speed at the source.

Thus for sources located near the sea surface the influence of the deep layers will vary with geographical location and season. The effect will be greatest in the winter when the near surface sound velocities are the lowest. In areas where the axis of the principal sound channel is shallow, as in the Mediterranean and Norwegian Seas, sources at modest depths (above or below the axis) can have a large bundle of rays propagating in the channel. Such rays can vertex a number of times at relatively modest ranges, both in the deep and thermocline layers.

For deep sources located well below the axis of the principal sound channel only the rays of positive source angle will be affected by the deep stepped structure. These are the only rays that will vertex in the deep layers within moderate ranges. The result is that in the North Atlantic for example, for receivers at less than 1000 m depths, only the reception beyond about 20 km will be affected.

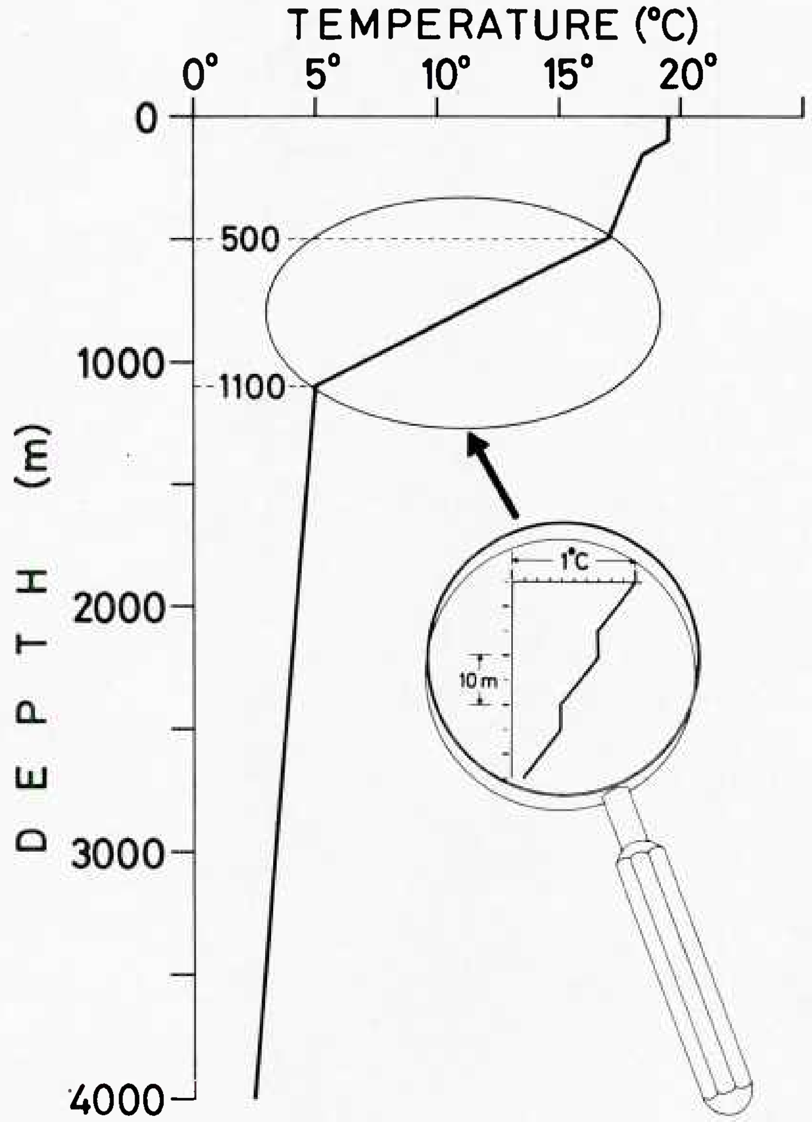


FIG. 11 SIMPLIFIED BERMUDA TEMPERATURE PROFILE. Indicated is also the type of microstructure inserted in the thermocline.

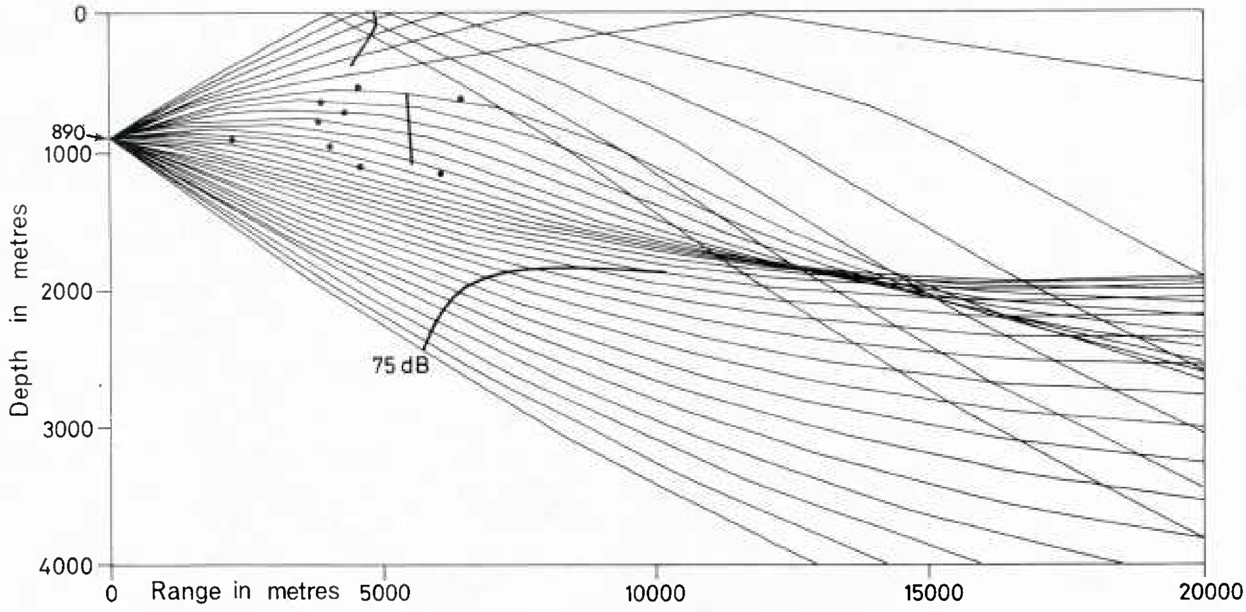


FIG. 12 RAY TRACING FOR BERMUDA PROFILE, SOURCE 890 m. Circles indicate 75 dB loss points for the profile with microstructure inserted in the thermocline.

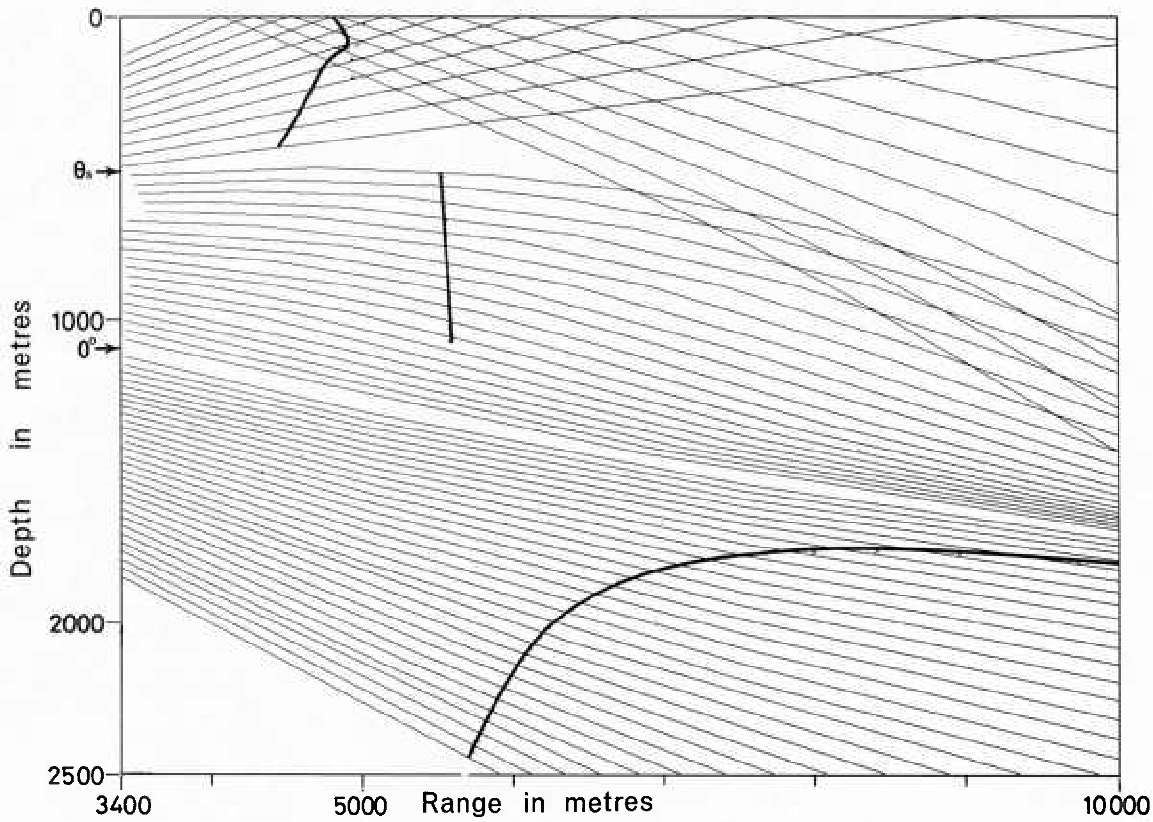


FIG. 13 75 dB LOSS CONTOURS FOR THE LINEAR BERMUDA PROFILE

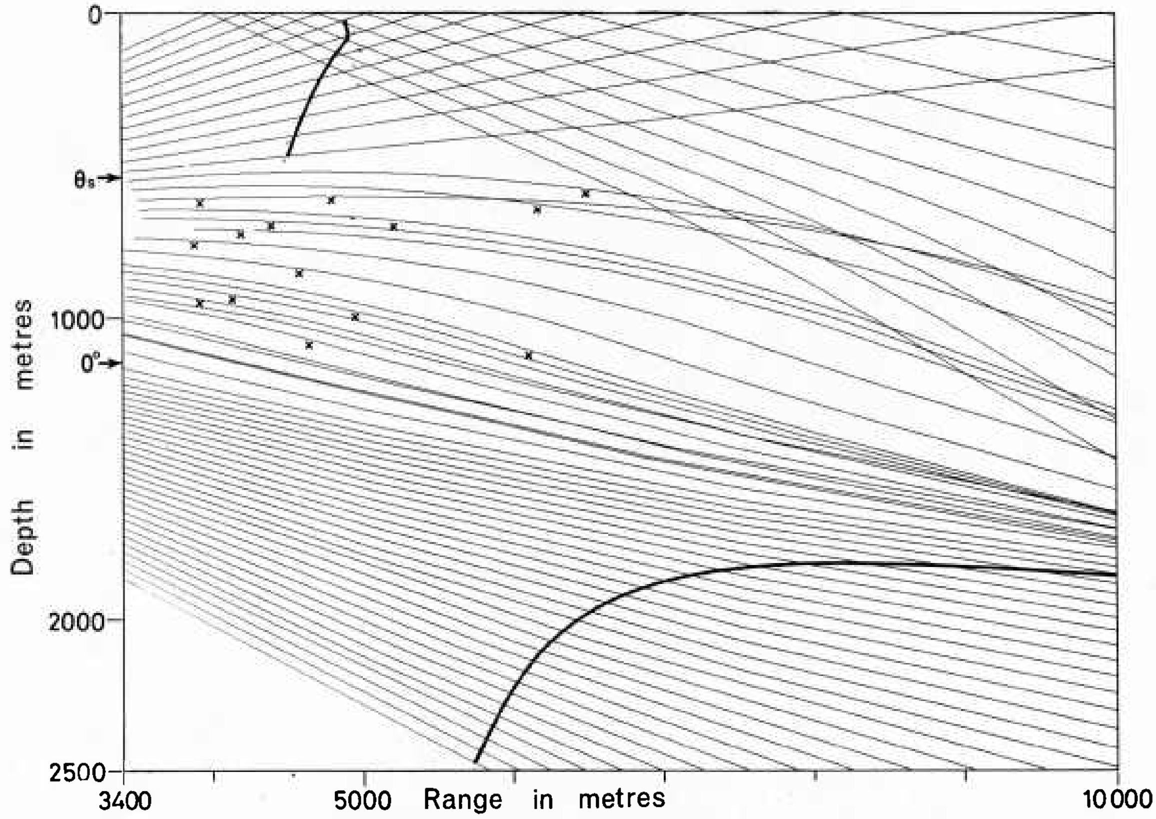


FIG. 14 75 dB LOSS CONTOURS FOR THE BERMUDA MICROSTRUCTURE PROFILE

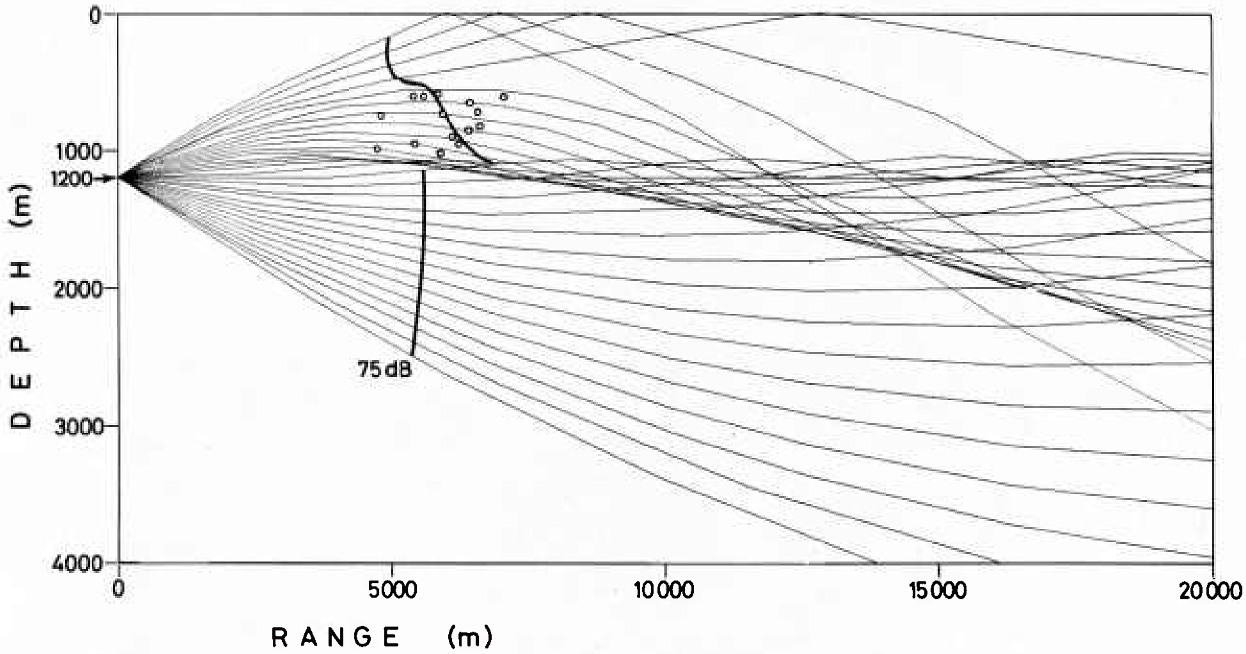


FIG. 15 RAY TRACING FOR THE BERMUDA PROFILE, SOURCE 1200 m. Circles indicate 75 dB loss points for the profile with the microstructure inserted in the thermocline.

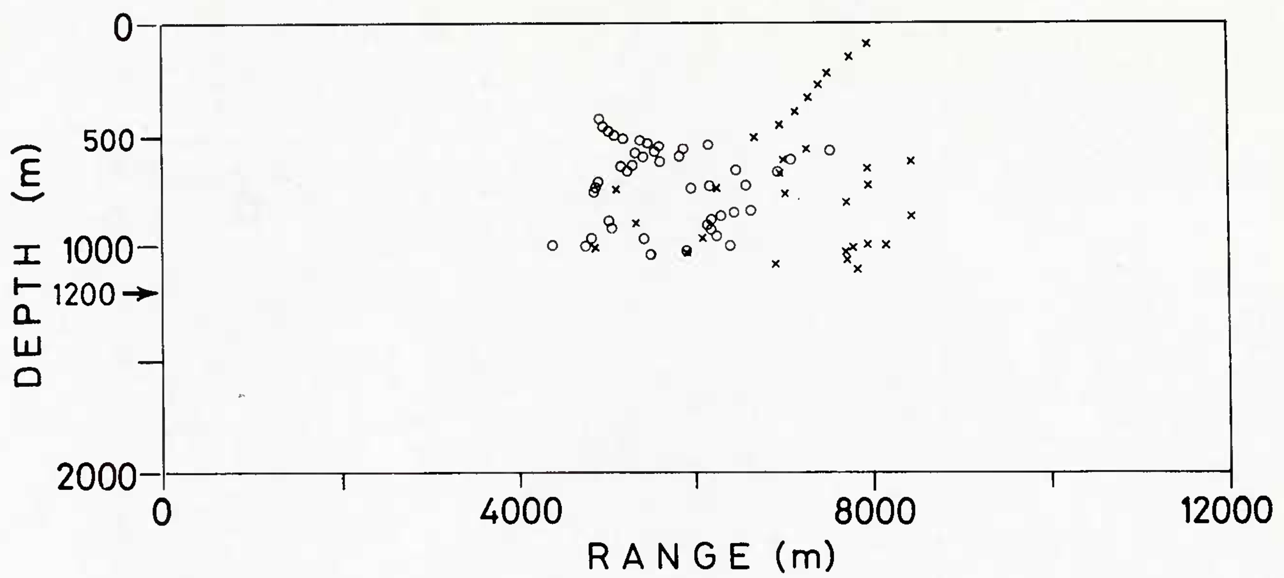


FIG. 16 LOSS POINTS FOR THE MICROSTRUCTURE BERMUDA PROFILE, 75 dB OPEN CIRCLES, 80 dB CROSSES, SOURCE 1200 m

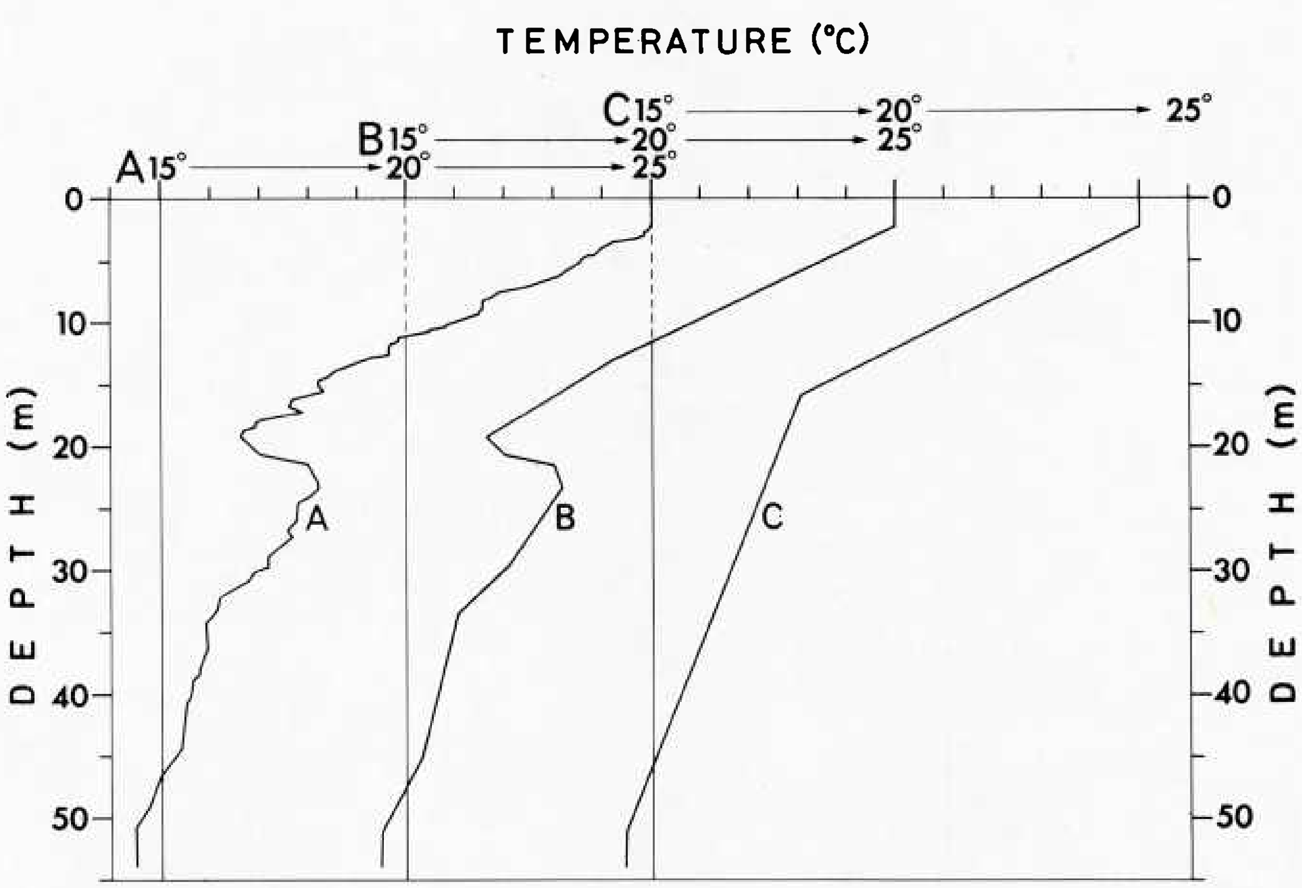


FIG. 17 APPROXIMATION OF THE WOODS MICROSTRUCTURE PROFILE IN FIG. 3

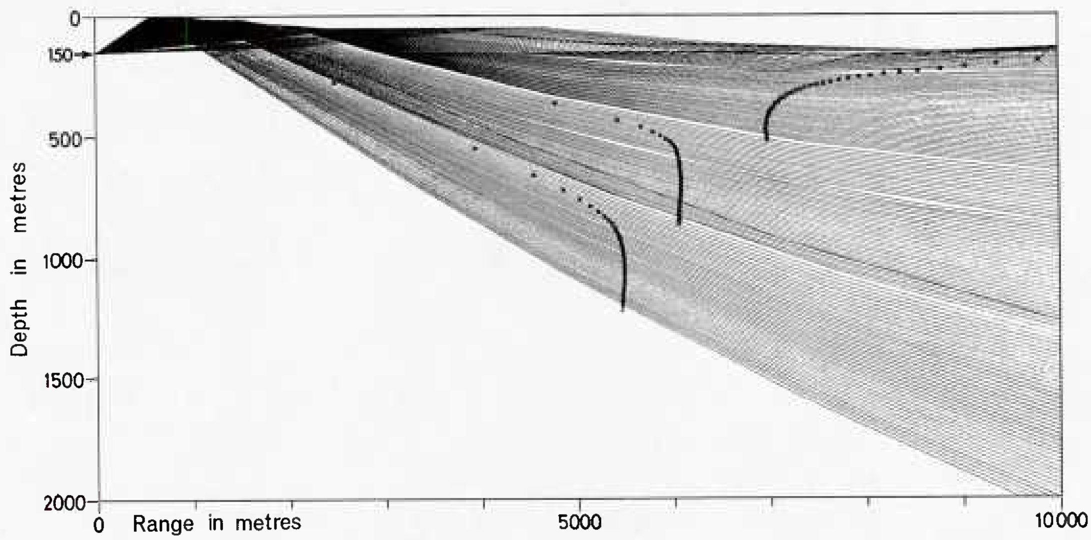


FIG. 18 RAY TRACING AND 75 dB LOSS CONTOURS FOR PROFILE C IN FIG. 17, SOURCE 150 m

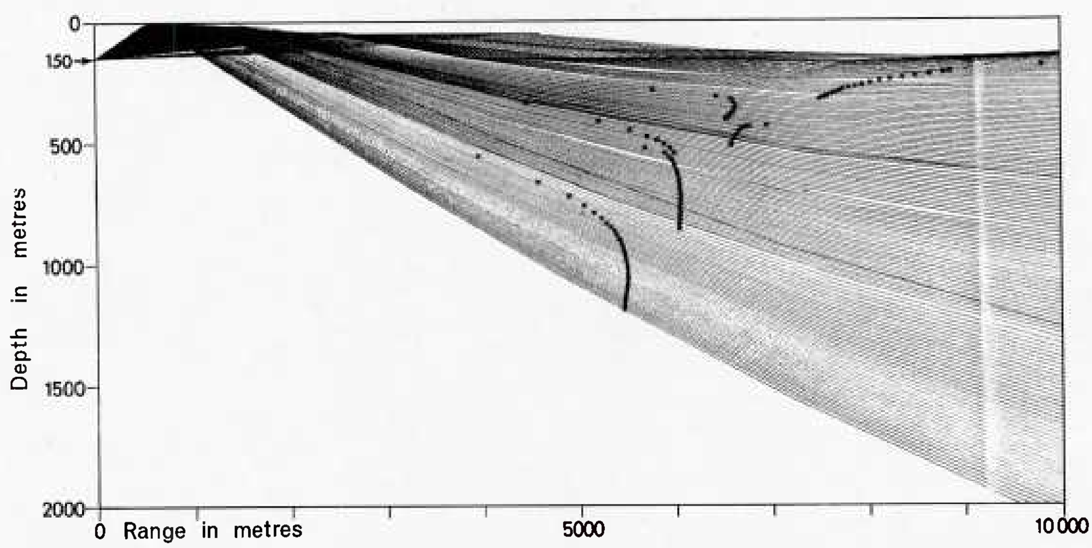


FIG. 19 RAY TRACING AND 75 dB LOSS CONTOURS FOR PROFILE B IN FIG. 17, SOURCE 150 m

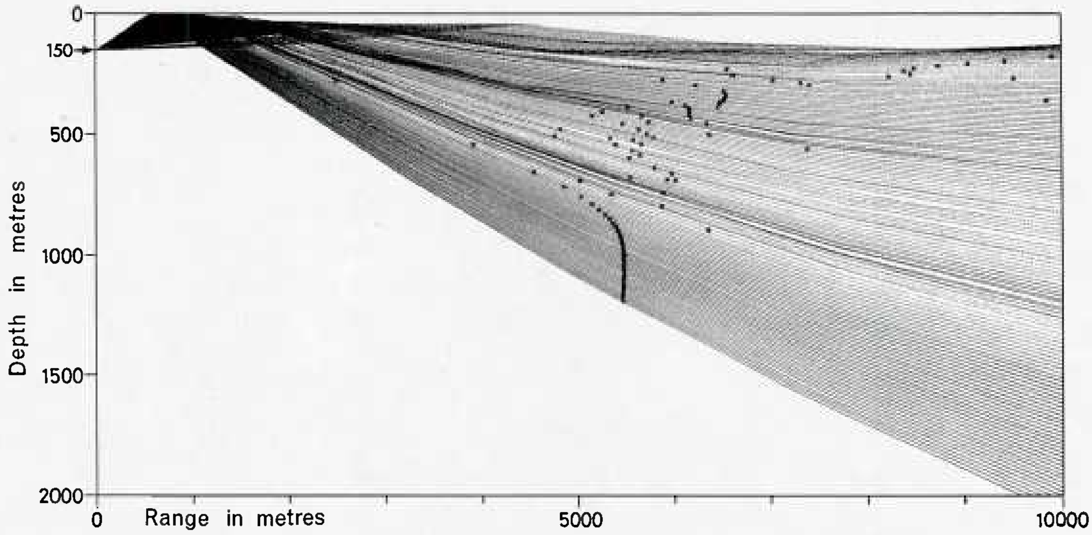


FIG. 20 RAY TRACING AND 75 dB LOSS CONTOURS FOR PROFILE A IN FIG. 17, SOURCE 150 m

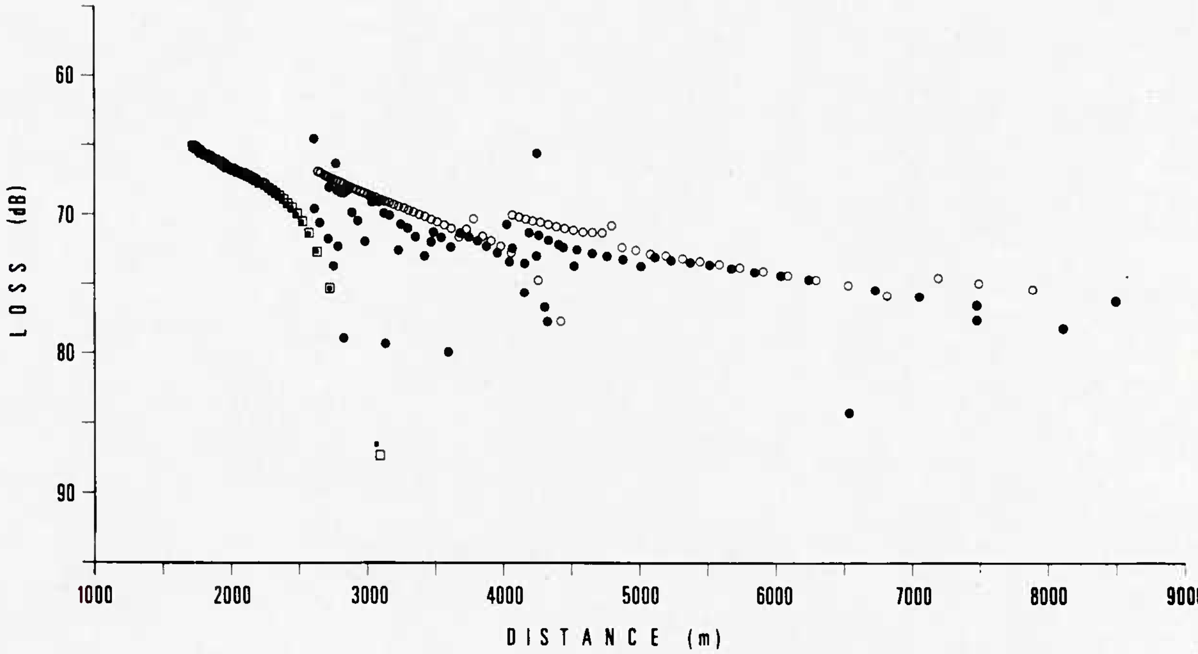


FIG. 21 PROPAGATION LOSS VS RANGE, DEPTH 300 m, SOURCE 150 m. Open symbols represent smoothed profile B in Fig. 17, and solid symbols the detailed profile A in Fig. 17.

3. DISCUSSION

A layered speed-of-sound structure is not unusual in the ocean. In general, ray tracing programs for computers are based on an approximation for the speed-of-sound profile using layers of constant speed gradient. Often no attention is paid to fine structure. The important feature taken into account in this study is the existence of a large number of quasi-isothermal or positive gradient layers, separated by interfacial layers of negative temperature gradients.

Ray tracing represents an approximation to actual sound propagation. The validity of the approximation is dependent upon wavelength. The wavelengths of interest in underwater acoustics range from less than 1 cm to more than 10 m. The question of validity therefore depends upon the particular propagation problem being considered along with the size and gradients of the microstructure.

In our models of the microstructure the thickness of the transition layers has varied from 5 m in one model to as small as 10 cm in others. The qualitative effect upon the sound field was the same. To reiterate, the common layered type of microstructure we examined had its predominant effect upon rays that had vertexed within the layers.

The presence of this type of microstructure caused the iso-intensity contours for these rays to degenerate into a broad scatter of points. As a result of this, when a source is varying its depth, the received signal that has travelled along rays that have vertexed in the microstructure, could exhibit rapid fluctuations. The magnitude of which will obviously vary with the depth of the source since the size of the ray bundle affected will vary. Similarly, the range at which the signal could be detected would change rapidly with changes in the depth of the source. As Fig. 21 shows, even when the source and receiver are at constant depths the signal level may vary erratically over small distances for microstructure vertexing rays.

Fluctuations such as those described above have been observed experimentally by Whitmarsh and Leiss [Ref. 25]. The found pulse-to-pulse amplitude differences of up to 15 dB for concurrent source and receiver depth changes of as little as 25 cm. Figure 22 is a reproduction of Fig. 2 in their article. On the left of this figure is the speed-of-sound depth profile. On the right, plotted as a function of depth, are the amplitude of the direct (non-reflected) 20 kHz signals as received at one deep-submergence freely sinking vehicle from another vehicle simultaneously sinking. The range between vehicles is 2377 m. Most of the large fluctuations in signal levels occur in the deep region where the speed-of-sound profile is changing most rapidly and is the most complex. Whitmarsh and Leiss suggest that such fluctuations are caused by the refractive properties of the medium and the mixing of multipath arrivals. Another possible factor is the phenomenon associated with thermocline vertexing rays which have been described in this study.

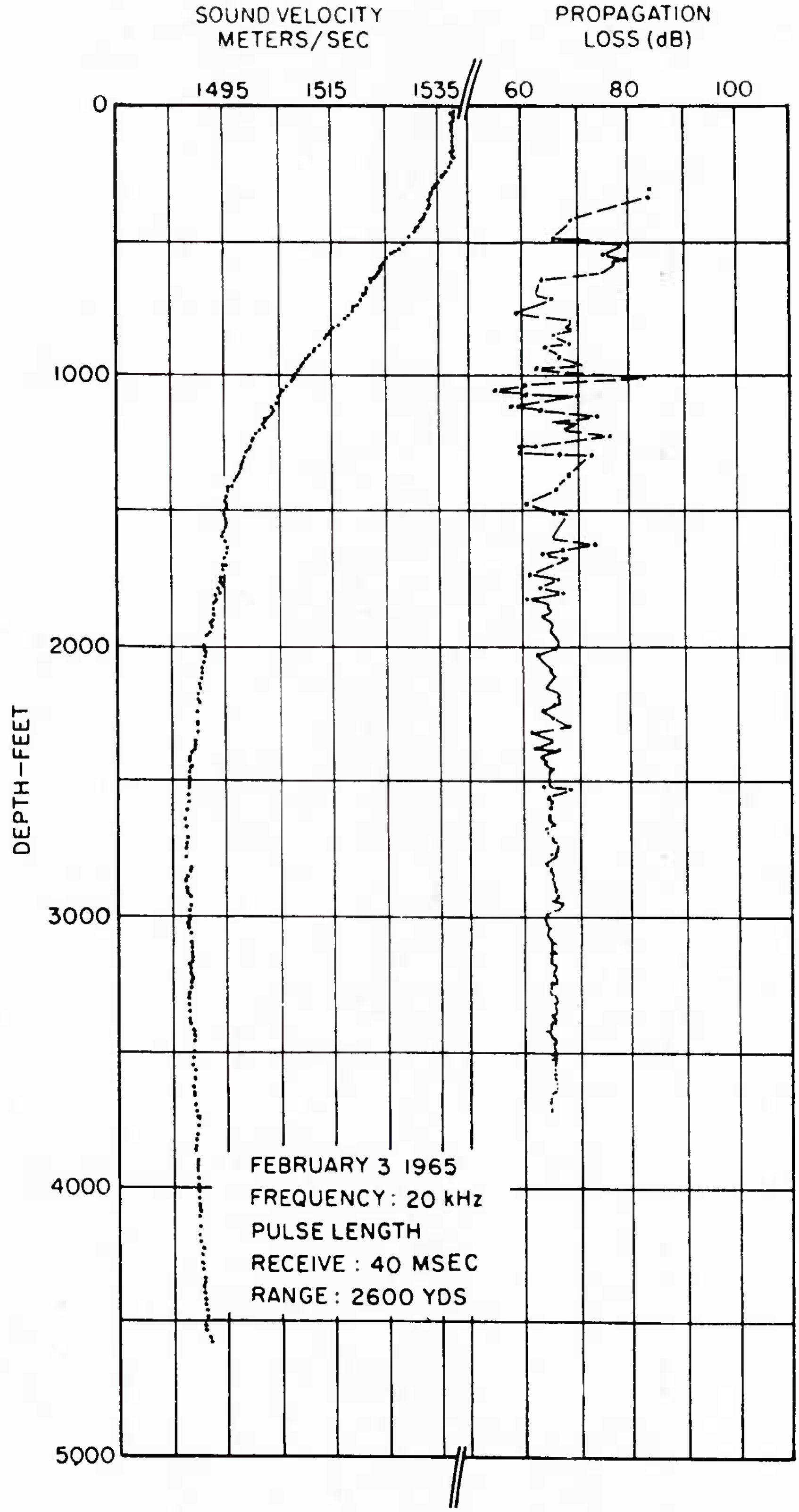


FIG. 22 TYPICAL TRANSMISSION–LOSS MEASUREMENTS AS A FUNCTION OF DEPTH. Measured sound velocity profile is at the left. (From Whitmarsh and Leiss, Ref. 25)

CONCLUSIONS

(1) The layered microstructure described in this report will have its predominant effect upon acoustic energy which has travelled along rays that have vertexed within the layers.

(2) The result will be the degeneration of the iso-intensity contours for these rays into a broad scatter of points. This will produce rapid and significant fluctuations in the received signal level for small changes in the spatial relationship between a source and receiver.

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